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PERFORMANCE OF THE TWO-LEVEL TARGETING ALGORITHM ON ARTEMIS I

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Artemis is NASA's campaign to explore the Moon and beyond. Artemis I, the uncrewed exoLEO test flight, was completed in 2022. This paper will summarize the performance of the onboard targeting algorithm, the two-level targeter (TLT), during the flight. The function of the TLT is to autonomously recompute the burn targets for the upcoming burn (or multiple burns) in response to navigation and vehicle dispersions, providing a solution that meets all of the trajectory constraints. Although the TLT has been utilized previously as a ground-based planning tool, the Artemis I mission is the first time it has been flown onboard. The lessons learned from TLT performance during Artemis I will help to inform the further development of the algorithm for future Artemis missions.

INTRODUCTION

The launch of the Artemis I mission on November 16, 2022 marked the first major milestone towards NASA's return to human exploration of the Moon and eventually Mars. The uncrewed, 25.5-day mission took the Orion spacecraft out past the Moon and into a stable Distant Retrograde Orbit (DRO), with a maximum distance of 233,375 nautical miles from the Earth. The trajectory included two powered lunar flybys, a 6-day stay in the DRO, and a novel set of entry target line constraints. Two views of the full trajectory in the Earth-Moon rotating frame are shown in Figures 1 and 2, with markers for each burn. The two figures also indicate the different mission stages and how the dynamics were modeled along the trajectory: the central gravitational body, and whether perturbations from spherical harmonics were considered to have a significant effect ("NEAR") or to be negligible ("FAR"). A key component of the Orion GN&C system was the Two-Level Targeter, or TLT, which performed onboard targeting for every burn in the Orbit phase of the mission (post-Upper Stage Separation through the final correction burn). The ability to accurately target burns onboard the vehicle is critical for exploration efforts beyond the Moon, as communication with the ground becomes more delayed and prone to dropouts. For Artemis I, the onboard targeting system was required to compute burn targets for a wide range of different trajectory constraints and in significantly disparate dynamical regimes, as shown in Figures 1 and 2. Although backup targets from ground computations were available, the expectation was that the onboard system would converge and produce a valid solution for every targeting pass.

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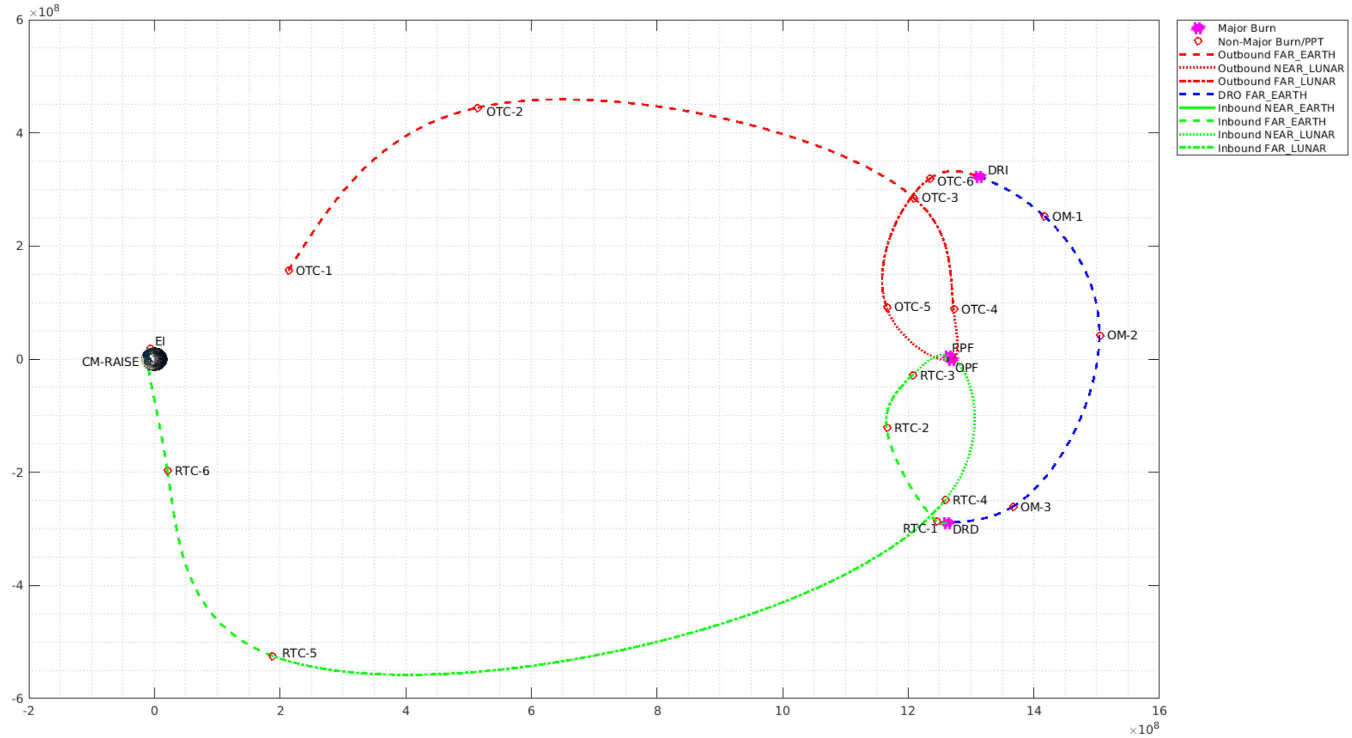


Figure 1: Top-down View of Artemis I Trajectory

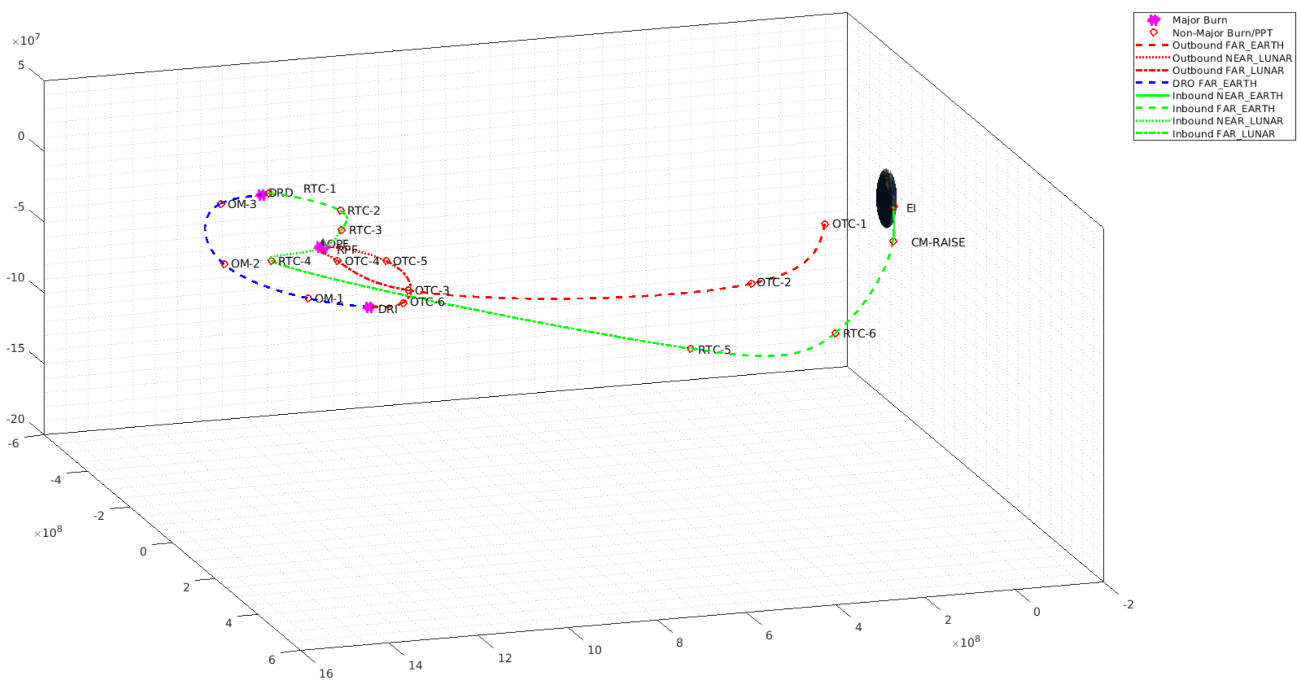
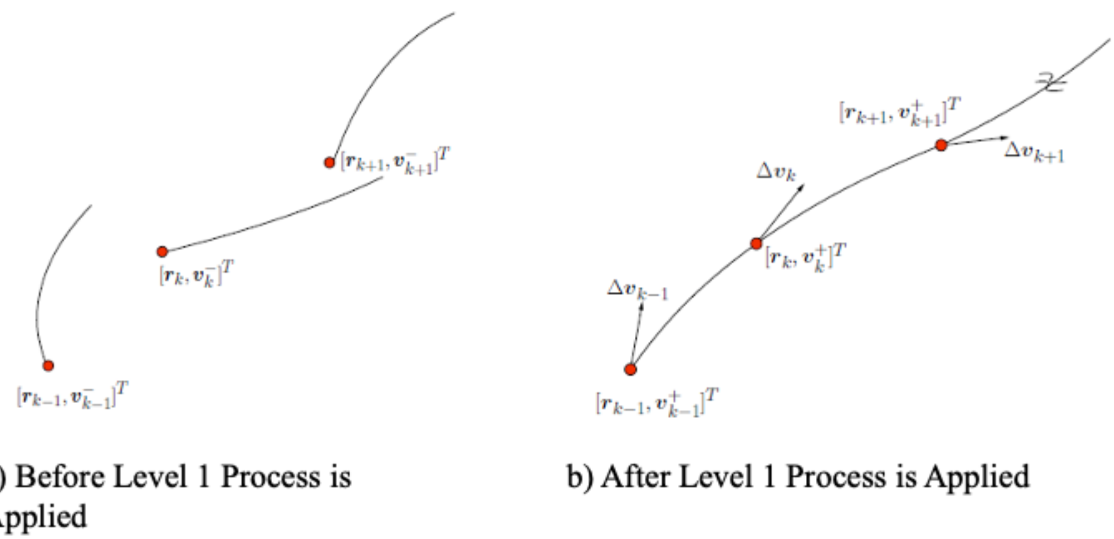


Figure 2: Angled View of Artemis I Trajectory Showing Out-of-Plane Motion

The purpose of this paper is to provide an overview of the Two-Level Targeter performance over the course of the mission. The metrics used for this initial evaluation are the convergence properties – both whether TLT converged at all and the number of iterations required for convergence – and a comparison of the onboard TLT ΔV solution to the ΔV that was computed using higher fidelity ground-based targeting tools. Discrepancies between the ground and onboard solutions and their possible causes will be briefly discussed, but in-depth analysis of specific results is reserved for future papers.

Two-Level Targeter Background

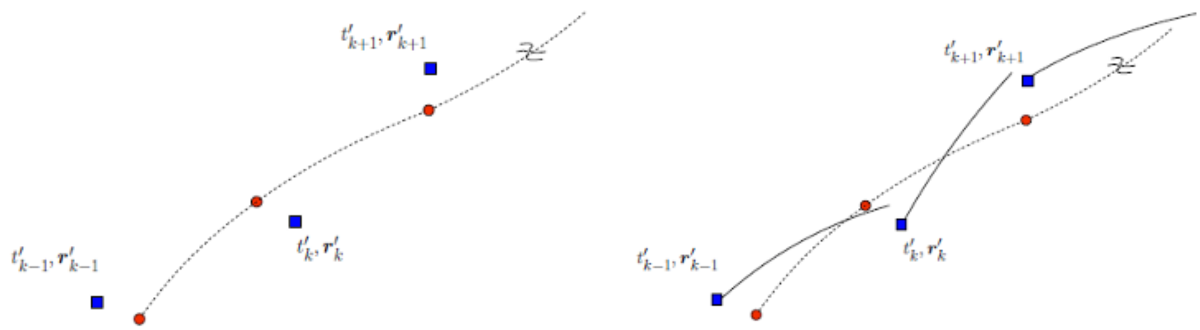
The Two-Level Targeter, or TLT, is a differential corrections method that utilizes a linearized dynamical model to compute updates to control parameters along the trajectory. An earlier version was used in the design of the Genesis mission trajectory,[1] but the Artemis I mission is the first time that it has flown as an onboard targeting algorithm. Of note, the TLT targeting passes for each burn simultaneously computed solutions for all of the remaining deterministic burns in the current trajectory segment as well, thus providing not only onboard targeting but also an onboard path replanning capability. This represents a significant advancement over previous onboard targeting algorithms that flew on Apollo and the Space Shuttle. The TLT uses a startup reference trajectory that is discretized into a set of N “patch points” or “patch states”. These patch states represent the vehicle state at certain points along the trajectory and typically coincide with points where there are burns or trajectory constraints (or both). This startup arc does not need to meet all of the path constraints, nor is it even required to be a feasible trajectory; it just needs to be a close enough guess that the linear updates can converge to a valid solution.[2,3] The algorithm consists of two main processes: the Level 1 process runs sequentially through the patch states, propagating each state to



the time of the next patch point and iteratively applying either an instantaneous delta-velocity (ΔV) or a burn arc to enforce position continuity along the trajectory.[4,5] A simplified visual representation of this process is provided in Figure 3.

Figure 3: Level 1 Process

After the Level 1 process is complete, the Level 2 process simultaneously adjusts the positions and times of each patch state to meet any applied trajectory constraints. Because the Level 2 process typically has more control parameters than constraints, a minimum norm solution is used to compute the desired updates.[2-5] A graphical representation of this is given in Figure 4.



a) Corrections Suggested by Level 2 Minimum Norm Solution

b) After Propagating the Level 2 Updated Patch States

Figure 4: Level 2 Process

Some examples of the Level 2 constraints include velocity continuity, flight path angle, periapse radius, and specialized entry target line constraints that were developed for the Artemis missions.[6] After the Level 2 updates are applied, the algorithm goes back through the Level 1 process to re-apply position continuity, then back to the Level 2 process, and continues to cycle iteratively through the Level 1 and Level 2 until it achieves a trajectory that is continuous in position and meets all of the applied trajectory constraints. For this paper, one full cycle through both the Level 1 and Level 2 processes is referred to as a “global” iteration. In addition to the Level 1 and Level 2 processes, the Orion TLT also includes an initialization routine to capture all the input data from various sources and condition it into a usable format for the algorithm, and a post-processing routine to map the TLT output patch states into appropriate burn targets for the Orion Orbit Guidance routine (OrbGuid).[7] The overall logic flow is shown in Figure 5.

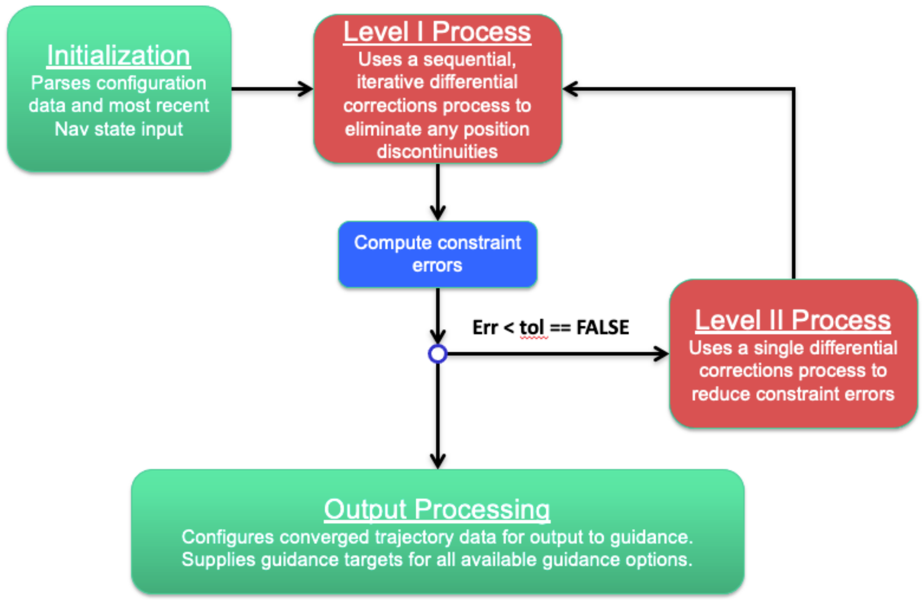


Figure 5: TLT Logic Flowchart

Concept of Operations for Artemis I

The Orion onboard TLT is used in conjunction with a burn plan developed by the Flight Control Team and managed by the Flight Dynamics Officer (FDO). This burn plan, which is derived from a ground-optimized trajectory, contains all the patch point data necessary for the TLT to run. The burn plan also contains other guidance and flight control data, including ground-computed targets that can be used by the guidance and controls systems in the event that the onboard TLT does not converge or returns a bad solution.[8] The Artemis I burn plans were split such that each one contained only the first half or second half of the trajectory. Burn plans for the first half of the trajectory ended in the DRO, so no entry constraints were applied for TLT targeting passes that used those burn plans. The update to include the second half of the trajectory of the burn plans occurred while the vehicle was in the DRO.

As part of the burn plan, all patch points are given a "type" designation that indicates how the TLT should process that particular patch state. The available patch point type enumerations are as follows:

- MAJOR_BURN – TLT is allowed to adjust the ΔV or burn parameters (initial direction, duration) for all targeting passes.
- CORRECTION_BURN – TLT applies a velocity constraint to this patch point unless it is the next burn in the sequence. The velocity constraint is typically 0 for velocity continuity, but could be non-zero in the case of a bias burn. When this type is the next burn in the sequence, TLT treats it as a MAJOR_BURN and can adjust the ΔV or burn parameters as necessary to meet constraints.
- GROUND_BURN – if this type is the next burn in the sequence, TLT does not run and will return non-convergence so as to avoid overwriting the ground targets in the burn plan. If it is further downstream, TLT will constrain the ΔV to match the value specified in the burn plan.
- NOT_A_BURN – TLT will always apply a velocity constraint to patch points of this type. If it is the next burn in the sequence, TLT will propagate ahead to target the next

valid burn. For Artemis I, this patch point type was used to designate the final patch state in the burn plan, which could not be a burn since there were no subsequent patch states for that burn to target. It can also be used to reduce the propagation time between patch points, which can help improve the accuracy of TLT's linear approximation in more nonlinear dynamical regions, or to specify non-burn events that affect the TLT computations. Examples of these events include a spring separation or crew waste dump, which would impart a non-modifiable ΔV to the vehicle, or Level 2 constraints that are not tied to a burn patch point.

- NOT_USED_IN_TLT – TLT ignores this patch point type altogether. It is not included in the patch point set that is fed to the algorithm. An example of this type in the Artemis I trajectory is the Command Module (CM) Raise burn; the Entry Interface constraints applied by TLT were computed to account for this burn without explicitly including it in the set of TLT patch points.

Any patch point type except for NOT_USED_IN_TLT can have constraints attached to it.

In addition to the burn plan, the onboard TLT takes its inputs from the current onboard navigation state and ephemeris data, the current vehicle mass estimate, and various constants and configuration parameters that have been uplinked to the vehicle. These values often differed from the input data being used for ground targeting, causing discrepancies between the ground and onboard solutions. A detailed analysis of these various error sources and their effect on the targeting comparisons is beyond the scope of this paper, but is the subject of future investigations.

For Artemis I, the onboard TLT solution was considered the prime solution. In other words, the onboard targets would be burned unless the FDO determined that the solution did not meet mission objectives. For converged targeting passes, the FDO evaluated the solution by plugging the burn solution into their ground-based ephemeris tool and then targeting the subsequent burn to determine the resulting ΔV magnitude. If the magnitude of the next burn was within acceptable limits, the onboard solution was burned.

There were three opportunities to run the TLT before each burn: preliminary targeting, which occurred approximately 3 hours before Time of Ignition (TIG); intermediate targeting, which was optional and could be anywhere from 1-2 hours before TIG; and final targeting, which automatically ran 31 minutes before TIG (71 minutes for the two flyby burns, to avoid communication blackout as the vehicle was behind the Moon at TIG-31 minutes). Burn plan and/or state vector uplinks could be performed before each execution of the TLT. Performance results for all three targeting passes are tabulated in each burn subsection. Convergence status indicates whether the TLT iteration loop converged on a solution. The number of global iterations executed by the TLT iteration loop is in the column titled "# of Global Iterations." The inertial International Celestial Reference Frame (ICRF) delta velocity (ΔV) vector computed by the TLT is given in the next column. The corresponding ΔV vector computed on the ground during determination of the burn plan is given next. Finally, constraints and the location in the trajectory where they were applied are listed. The constraint types used for the Artemis I mission were radius of periapse (Rp), absolute time (T), position (x, y, and z components: Rx, Ry, Rz), geodetic altitude (Alt), and the entry horizontal and vertical target lines (HTL, VTL).

ALGORITHM PERFORMANCE FOR MAJOR BURNS

The Artemis I trajectory was defined by four "major" burns following the trans-lunar injection burn (TLI), which was not targeted by Orion. The first, the Outbound Powered Flyby, or OPF, was performed as Orion made its closest approach to the Moon and was intended to set the vehicle on a course to intercept the DRO. The next major burn, Distant Retrograde Orbit Insertion (DRI), placed the vehicle into the stable DRO. The DRO Departure burn, DRD, broke Orion out of the

DRO and onto a trajectory back towards the Moon for the Return Powered Flyby, or RPF, which was the final major burn to get the vehicle on course for Entry Interface (EI). The onboard TLT was used to compute burn targets for all four of these deterministic burns. The performance of the targeter for each one will be discussed in the subsections below.

Outbound Powered Flyby (OPF)

Although the TLT had already run successfully onboard for four correction burns prior to OPF, including the 30 second Orion Main Engine (OME) checkout burn during the first correction burn, the OPF targeting passes represented the first significant test for the targeter. Due to the close approach to the Moon, the vehicle dynamics were highly nonlinear and highly sensitive – even minor differences in the navigation state and the environment modeling (spherical harmonics, etc.) would have a significant effect when propagated out to the time of the next patch point. This presented challenges both for convergence and for good matching with Ground targets. In addition, there was a small inconsistency in the burn plan: the burn plan DRI patch point position did not match the position vector constraint imposed on the DRI patch point. This compounded the discrepancy induced by the differing navigation states by adding a slight rotation (approximately 2 degrees) in the onboard TLT ΔV solution vector as compared to the burn plan vector. The ΔV magnitude, however, matched the burn plan very closely. Overall, the TLT performance for OPF was very good. The targeter converged in 2 iterations for all targeting passes, and the solution was a good match to the expected targets computed on the ground given the various sources of error. A summary of the targeting results is given in Table 1. There was a ground update to the onboard navigation state prior to final targeting; this caused minor changes in the ΔV solution both from the onboard TLT and in the ground targeting.

Table 1: OPF Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	-190.381 -501.919 -237.978 *Magnitude: 587.198*	-168.589 -507.338 -242.410 *Magnitude: 587.007*	DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T
Intermediate	CONVERGED	2	-190.447 -501.899 -237.967 *Magnitude: 587.197*	-168.589 -507.338 -242.410 *Magnitude: 587.007*	DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T
Final	CONVERGED	2	-189.074 -499.817 -241.143 *Magnitude: 586.273*	-167.358 -505.175 -245.509 *Magnitude: 586.077*	DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T

Distant Retrograde Orbit Insertion (DRI)

Because the dynamics at the distant retrograde orbit are very favorable (i.e. close to linear), the DRI and DRD burns were particularly well-suited to a linear algorithm like the TLT. Furthermore, the environment modeling onboard was closer to the ground model since the spherical harmonics of the Earth and the Moon do not have a significant effect so far away. For the DRI burn, the only trajectory constraint imposed was the position vector and patch point time at DRD. Although there was again a mismatch between the specified patch point position and the desired constraint value in the burn plan, the discrepancy was minimal and did not affect the TLT solution. The targeter converged in 2 iterations for all targeting passes, and produced very close matching between the onboard TLT and the Ground targets. The performance is summarized in Table 2. Although the onboard navigation state did receive a ground update before the final targeting pass, the change to the state was not significant enough to require a burn plan update and the effect on the onboard targeting solution was minimal.

Table 2: DRI Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	-157.226 -297.317 -136.551 *Magnitude: 362.993*	-157.202 -297.246 -136.451 *Magnitude: 362.887*	DRD: Rx, Ry, Rz, T
Intermediate	CONVERGED	2	-157.228 -297.336 -136.582 *Magnitude: 363.020*	-157.202 -297.246 -136.451 *Magnitude: 362.887*	DRD: Rx, Ry, Rz, T
Final	CONVERGED	2	-157.188 -297.192 -136.478 *Magnitude: 362.846*	-157.202 -297.246 -136.451 *Magnitude: 362.887*	DRD: Rx, Ry, Rz, T

Distant Retrograde Orbit Departure (DRD)

Similar to the DRI targeting passes, DRD targeting benefitted from favorable dynamics and reduced sources of error in propagation modeling. However, the constraint set for this burn included the two EI target line constraints, horizontal (HTL) and vertical (VTL); this was the first time in the mission that these constraints had been applied and processed in the onboard TLT. In running the return leg targeting passes, it was noted that there was a mismatch of about 0.5 seconds between the onboard Mission Elapsed Time (MET) reference epoch and the one used for ground targeting; this manifested in the HTL constraint error calculation since the HTL components are computed in an Earth-fixed frame. The HTL adjustment required an additional global iteration to correct, but the targeter was still substantially below its maximum iteration limit. Table 3 shows the convergence results and ΔV comparisons for each DRD targeting pass. For this burn, there was no ground update to the onboard navigation before final targeting.

Table 3: DRD Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	3	453.785 -20.817 4.048 *Magnitude: 454.281*	454.255 -20.926 4.254 *Magnitude: 454.757*	RPF: Rp, T EI: Alt, HTL, VTL
Intermediate	CONVERGED	3	453.761 -20.810 3.978 *Magnitude: 454.255*	454.255 -20.926 4.254 *Magnitude: 454.757*	RPF: Rp, T EI: Alt, HTL, VTL
Final	CONVERGED	3	453.743 -20.819 3.936 *Magnitude: 454.237*	454.255 -20.926 4.254 *Magnitude: 454.757*	RPF: Rp, T EI: Alt, HTL, VTL

Return Powered Flyby (RPF)

This was the final major burn before EI. Although there were still three correction burns prior to the EI patch point, at the time of RPF targeting, each of these burns was constrained to have a 0 ft/s ΔV per the standard TLT enforcement of velocity continuity at correction burn patch points. This limited the solution space because the number of constraints at EI was essentially equal to the number of independent control parameters – in this case the RPF burn parameters – with which to modify the trajectory. The HTL error stemming from the MET epoch discrepancy did still result in 3 global iterations being required for convergence, and it also caused minor rotation of the ΔV vector as compared to the burn plan vector. Despite these challenges, the onboard TLT performance was very good, as shown in Table 4. The optional intermediate targeting pass was skipped for this burn, as was the navigation state vector update.

Table 4: RPF Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	3	860.542 -185.657 -386.880 *Magnitude: 961.601*	872.807 -150.947 -373.848 *Magnitude: 961.426*	EI: Alt, HTL, VTL
Intermediate	N/A	N/A	N/A	N/A	N/A
Final	CONVERGED	3	860.259 -184.988 -386.021 *Magnitude: 960.873*	872.807 -150.947 -373.848 *Magnitude: 961.426*	EI: Alt, HTL, VTL

ALGORITHM PERFORMANCE FOR CORRECTION BURNS

The Artemis I trajectory also contained trajectory correction burns on both the outbound (Outbound Trajectory Correction, or OTC burns), DRO (Orbit Maintenance, or OM burns), and return (Return Trajectory Correction, or RTC burns) legs. These were primarily very small burns intended to reduce dispersions, but some correction burns were used to test various aspects of the propulsion and control systems.

OTC-1

The preliminary targeting pass for OTC-1 was the first flight run of the onboard TLT. The burn plan included patch points and burns all the way out to the DRO, so TLT was solving multiple trajectory constraints simultaneously – periapse radius and time at OPF, and inertial position vector and time at DRI and DRD, along with enforcing velocity continuity at the other outbound correction burn patch points. The OTC-1 burn also served as the main engine (OME) checkout burn. This burn had a minimum duration requirement of 30 seconds in order to perform a sufficient assessment of the OME. Burn duration is not currently a directly enforceable constraint in the onboard TLT. The predicted burn duration of the onboard TLT solution after final targeting was 30.43 seconds. The optional intermediate targeting pass and the navigation state vector update were skipped for this burn. The results for each targeting pass are given in Table 5.

Table 5: OTC-1 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	-36.274 96.271 50.608 *Magnitude: 114.652*	-36.308 96.377 50.543 *Magnitude: 114.723*	OPF: Rp, T DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T
Intermediate	N/A	N/A	N/A	N/A	N/A
Final	CONVERGED	2	-36.288 96.021 50.720 *Magnitude: 114.496*	-36.308 96.377 50.543 *Magnitude: 114.723*	OPF: Rp, T DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T

OTC-2

The OTC-2 burn was targeted successfully as a small Service Module Reaction Control System (SM RCS) burn. Results are shown in Table 6. Preliminary targeting resulted in a close match to the burn plan velocity. Since modeling of SM RCS thrust is different onboard with respect to ground tools, some burn duration differences were observed and attributed to a simpler method used onboard. This did not impact burn performance. As with OTC-1, OTC-2 intermediate targeting was skipped since the FDO deemed it was unnecessary. The final targeting solution had significantly different ΔV components but similar magnitude which only changed by approximately 0.17 fps. The onboard TLT targets were selected for use in burn execution.

Table 6: OTC-2 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	0.444 -0.297 -0.466 *Magnitude:* *0.709*	0.453 -0.215 -0.526 *Magnitude:* *0.726*	OPF: Rp, T DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T
Intermediate	N/A	N/A	N/A	N/A	N/A
Final	CONVERGED	2	0.040 -0.656 -0.591 *Magnitude:* *0.884*	0.453 -0.215 -0.526 *Magnitude:* *0.726*	OPF: Rp, T DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T

OTC-3

The third trajectory correction maneuver on the outbound portion of the trajectory was the first instance where all three targeting passes were performed onboard prior to the execution of the burn. Before preliminary targeting, an updated burn plan was uplinked to the spacecraft and this same burn plan was employed for all three onboard targeting passes. The onboard solutions vary only slightly across the three targeting passes due to small changes in computed navigation states provided to the TLT, most notably in the final targeting pass due to a navigation state vector update from the ground navigation. The results from the targeting passes associated with this burn, given in Table 7, demonstrated an entirely nominal performance by the onboard targeting algorithm.

Table 7: OTC-3 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	2.568 0.860 -1.122 *Magnitude:* *2.931*	2.565 0.934 -1.165 *Magnitude:* *2.968*	OPF: Rp, T DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T
Intermediate	CONVERGED	2	2.582 0.855 -1.097 *Magnitude:* *2.933*	2.565 0.934 -1.165 *Magnitude:* *2.968*	OPF: Rp, T DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T
Final	CONVERGED	2	2.731 0.525 -0.980 *Magnitude:* *2.949*	2.565 0.934 -1.165 *Magnitude:* *2.968*	OPF: Rp, T DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T

OTC-4

The execution of this correction maneuver was important for setting the spacecraft up in an appropriate position to perform the quickly approaching Outbound Powered Flyby. Targeting results are listed in Table 8; the deviation of the onboard solution from the burn plan appears just slightly larger than was observed for OTC-3, suggesting a slightly larger difference between the ground and onboard navigation states. However, the burn sizes are still quite small and remain below one foot per second indicating that the spacecraft is in a good location for OPF. The onboard targeter again converged almost immediately and functioned nominally, even with the larger discrepancy between the initial guess trajectory and the estimated vehicle state. The optional intermediate targeting pass was skipped for this burn.

Table 8: OTC-4 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	-0.079 0.856 0.260 *Magnitude:* *0.899*	-0.140 0.945 0.174 *Magnitude:* *0.972*	OPF: Rp, T DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T
Intermediate	N/A	N/A	N/A	N/A	N/A
Final	CONVERGED	2	-0.116 0.816 0.223 *Magnitude:* *0.853*	-0.140 0.945 0.174 *Magnitude:* *0.972*	OPF: Rp, T DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T

OTC-5

After the completion of the Outbound Powered Flyby, the constraints applied to that patch point are no longer required. Therefore, in the case of OTC-5, the imposed constraints include inertial position vector and time at both DRI and DRD, along with constraining other correction burns to have zero ΔV. In this situation, an updated burn plan was not uplinked to the spacecraft until shortly before final targeting. Therefore, for both preliminary and intermediate targeting, the burn plan from OPF was employed. However, in the OPF burn plan, the values for the OTC-5 ΔV components were set to zero since OTC-5 is a correction burn with a desired ΔV of zero. With no ΔV provided by the burn plan, the Onboard TLT does not have a specifically defined initial guess and so is free to move in any manner that provides a feasible solution satisfying all constraints. However, this lack of a quality initial guess did not adversely affect the algorithm's performance for either preliminary or intermediate targeting. In each case, the algorithm converged in only two iterations. A navigation state vector update was uplinked to the vehicle between preliminary and intermediate targeting, bringing the onboard solution closer to the ground ΔV targets that would eventually be uplinked with the new burn plan prior to final targeting. Results for each targeting pass are listed in Table 9.

Table 9: OTC-5 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	1.969 0.191 0.730 *Magnitude:* *2.109*	0 0 0 *Magnitude:* *0*	DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T
Intermediate	CONVERGED	2	3.227 0.182 0.842 *Magnitude:* *3.340*	0 0 0 *Magnitude:* *0*	DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T
Final	CONVERGED	2	3.231 0.161 0.851 *Magnitude:* *3.345*	3.137 0.118 0.809 *Magnitude:* *3.242*	DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T

OTC-6

This maneuver was the last correction opportunity prior to entering the Distant Retrograde Orbit. The onboard solutions computed during preliminary and final targeting both agree closely with the burn plan indicating that the navigation state is in close proximity to the baseline trajectory. The targeting algorithm converged in two iterations in each pass exhibiting nominal behavior. The optional intermediate targeting pass was skipped for this burn, and the onboard navigation state was not updated at any point between preliminary and final targeting. Table 10 gives the results for each OTC-6 targeting pass.

Table 10: OTC-6 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	1.528 3.497 -8.051 *Magnitude:* *8.909*	1.546 3.492 -8.054 *Magnitude:* *8.914*	DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T
Intermediate	N/A	N/A	N/A	N/A	N/A
Final	CONVERGED	2	1.507 3.461 -8.109 *Magnitude:* *8.945*	1.546 3.492 -8.054 *Magnitude:* *8.914*	DRI: Rx, Ry, Rz, T DRD: Rx, Ry, Rz, T

OM-1

The Orbital Maintenance maneuvers were expected to be small and uneventful, as the DRO orbit is very dynamically stable. That was true in the case of the first OM burn. In this case all three targeting passes employed the same burn plan, the onboard navigation state was not updated after preliminary targeting, and all three passes exhibited rapid convergence as shown in Table 11.

Table 11: OM-1 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	-0.099 0.119 0.288 *Magnitude:* *0.327*	-0.060 0.219 0.354 *Magnitude:* *0.420*	DRD: Rx, Ry, Rz, T
Intermediate	CONVERGED	2	-0.116 0.111 0.232 *Magnitude:* *0.282*	-0.060 0.219 0.354 *Magnitude:* *0.420*	DRD: Rx, Ry, Rz, T
Final	CONVERGED	2	-0.138 0.095 0.221 *Magnitude:* *0.277*	-0.060 0.219 0.354 *Magnitude:* *0.420*	DRD: Rx, Ry, Rz, T

OM-3

The mission proceeded from OM-1 directly to OM-3 since the second scheduled Orbital Maintenance burn was cancelled and thus removed from the burn plan. Also at this point in the mission, a test objective was proposed to exercise a different thruster configuration; this represented a significant departure from the nominal burn plan. Therefore, the flight control team manually designed a burn to support the test objective. In order to execute the newly computed burn, the OM-3 maneuver was specified to be a GROUND_BURN. In this situation, the onboard targeting algorithm is expected to detect the burn type and terminate without performing any targeting computations and without modifying the specified burn. This is exactly what the onboard software did. Although this maneuver did not require onboard targeting, it did provide an opportunity to test the onboard algorithm logic and successfully skipped this burn as designed.

As part of the design process for computing the new OM-3 burn, the remainder of the trajectory was reoptimized; this was the process used for abort or off-nominal trajectories. This provided a good test of the TLT for the entire return leg, as the reoptimized set of patch points now differed from those used in pre-mission data generation and testing. Another item to note for the subsequent set of RTC targeting passes is that now the onboard targeter was subject to the constraints associated with the Entry Interface patch point. These constraints include altitude, horizontal target line, and vertical target line. As mentioned above in the DRD section, a 0.5 second discrepancy was noticed between the onboard reference epoch and the one used for ground targeting, resulting in the targeter requiring an additional global iteration for some of the RTC targeting passes to satisfy the HTL constraint.

RTC-1

The first Return Trajectory Correction maneuver provided an interesting scenario regarding the onboard targeting algorithm. As usual, an updated burn plan was uplinked to the spacecraft prior to preliminary targeting and this burn plan was used for both preliminary and intermediate targeting. However, shortly before final targeting, the flight control team computed an updated navigation state on the ground which they did not have time to uplink to the spacecraft. Without the new navigation state, the onboard targeting algorithm would have used an onboard value for the navigation state and would have likely functioned normally and produced a solution similar to those obtained from the previous two targeting passes. However, the newly computed navigation state was significantly different from the onboard value relative to the size of the burn. This placed the spacecraft in a different location from where the onboard TLT thought it was. Although the spacecraft was not going to be informed of the newly computed navigation state due to uplink time limitations, the flight control team was able to use the latest navigation state in their targeting computations on the ground. Therefore, the decision was made to follow the ground-computed targeting solution which was based on newer navigation state information. To implement the ground solution, a new burn plan was uplinked to the spacecraft with the ground-computed burn information and the RTC-1 maneuver was changed to a GROUND_BURN. In the case of a GROUND_BURN, the onboard targeting algorithm detects the burn type and then terminates without performing any targeting calculations. Therefore, as shown in Table 12, the final targeting pass returns NOT CONVERGED since the algorithm is directed not to work with these types of burn plans. Again, the algorithm logic performed as designed.

Table 12: RTC-1 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	3	0.125 -0.402 -0.082 *Magnitude:* *0.428*	0.119 -0.399 -0.080 *Magnitude:* *0.424*	RPF: Rp, T EI: Alt, HTL, VTL
Intermediate	CONVERGED	3	0.123 -0.400 -0.080 *Magnitude:* *0.426*	0.119 -0.399 -0.080 *Magnitude:* *0.424*	RPF: Rp, T EI: Alt, HTL, VTL
Final	NOT CONVERGED (Ground burn)	N/A	N/A	0.055 -0.569 -0.184 *Magnitude:* *0.601*	RPF: Rp, T EI: Alt, HTL, VTL

RTC-2

For this set of targeting passes, the onboard algorithm functioned nominally. The two computed solutions differ slightly from the provided burn plan initial guess but remain consistent with each other between the two targeting passes, since there was no ground update to the onboard navigation state. The results for the RTC-2 targeting passes are listed in Table 13.

Table 13: RTC-2 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	3	-0.202 -1.677 0.685 *Magnitude:* *1.823*	-0.092 -1.562 0.788 *Magnitude:* *1.752*	RPF: Rp, T EI: Alt, HTL, VTL
Intermediate	N/A	N/A	N/A	N/A	N/A
Final	CONVERGED	3	-0.242 -1.681 0.658 *Magnitude:* *1.821*	-0.092 -1.562 0.788 *Magnitude:* *1.752*	RPF: Rp, T EI: Alt, HTL, VTL

RTC-3

For the third Return Trajectory Correction, the targeting algorithm again functioned nominally. Interestingly, the magnitude of the computed solutions display a small amount of growth as the targeting passes progress, as shown in Table 14. This growth is likely due to changes in the navigation state relative to the baseline trajectory as also noted previously and was no cause for concern in this situation.

Table 14: RTC-3 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	3	-0.061 1.517 -1.414 *Magnitude:* *2.075*	0.225 1.937 -1.196 *Magnitude:* *2.287*	RPF: Rp, T EI: Alt, HTL, VTL
Intermediate	CONVERGED	3	-0.090 1.495 -1.461 *Magnitude:* *2.092*	0.225 1.937 -1.196 *Magnitude:* *2.287*	RPF: Rp, T EI: Alt, HTL, VTL
Final	CONVERGED	3	0.148 1.701 -1.339 *Magnitude:* *2.170*	0.225 1.937 -1.196 *Magnitude:* *2.287*	RPF: Rp, T EI: Alt, HTL, VTL

RTC-4

The 4th return trajectory correction burn was targeted successfully following the Return-Powered-Flyby burn. A new burn plan was provided and all three targeting passes were performed (see results in Table 15). A ground state update was performed prior to final targeting which lowered the ΔV since the navigation state moved closer to the plan. This burn was performed on SM RCS and represents the first correction on the return leg after the final major burn.

Table 15: RTC-4 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	3	-0.044 1.029 -0.604 *Magnitude:* *1.194*	-0.047 1.008 -0.611 *Magnitude:* *1.18*	EI: Alt, HTL, VTL
Intermediate	CONVERGED	3	-0.030 1.030 -0.618 *Magnitude:* *1.201*	-0.047 1.008 -0.611 *Magnitude:* *1.18*	EI: Alt, HTL, VTL
Final	CONVERGED	3	0.157 0.625 -0.125 *Magnitude:* *0.656*	0.144 0.603 -0.126 *Magnitude:* *0.633*	EI: Alt, HTL, VTL

RTC-5

The RTC-5 burn was targeted successfully following several days of cis-lunar coast in preparation for the final earth approach. During the days preceding RTC-5, a new burn plan was built using a re-optimized set of patch states, which cleaned up some of the error in the HTL constraint that had been causing the TLT to need a third global iteration to converge. In addition, though, multiple Demonstration Flight Test Objectives (DFTOs) were executed, some of which may have imparted some residual ΔV on the Orion vehicle. Ground targeting listed a 5.1 ft/s burn and noted that if skipped, the resulting RTC-6 burn would climb from near 0 ft/s to about 33 ft/s. The burn plan was updated with configuration for this burn as an AUX8 burn. Preliminary and final targeting converged in 2 iterations while optional intermediate targeting was skipped, as shown in Table 16. It was noteworthy that both RTC-5 and the subsequent RTC-6 burn were configured as non-critical since the respective EI performance was nominal. No ground navigation state update was performed and the burn was executed using onboard targets from the final targeting solution derived from the same plan as preliminary targeting.

Table 16: RTC-5 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	2.636 3.629 -2.487 *Magnitude:* *5.129*	2.501 3.782 -2.471 *Magnitude:* *5.164*	EI: Alt, HTL, VTL
Intermediate	N/A	N/A	N/A	N/A	N/A
Final	CONVERGED	2	2.685 3.558 -2.653 *Magnitude:* *5.187*	2.501 3.782 -2.471 *Magnitude:* *5.164*	EI: Alt, HTL, VTL

RTC-6

The RTC-6 burn was targeted successfully and represented the final orbit correction burn prior to Entry Interface. Table 17 shows the results for each targeting pass. Early onboard targeting post-RTC-5 showed a 0.27 fps ΔV and 3 iterations for RTC-6. A new burn plan was provided prior to preliminary targeting with an AUX8 configuration after some discussion about contingencies associated with communications loss and burn modeling. This was to ensure that the onboard automation would execute the RTC-6 burn in the event of a comm loss, as a no-burn would have resulted in a degraded entry state. Intermediate targeting was successful without a ground state update to the navigation system. A new burn plan was provided after intermediate targeting which retained the AUX8 setting and updated ground targets. After successful final targeting of RTC-6 onboard, the FDO determined that performance was more favorable if selecting the ground targets since they had the benefit of the latest ground prediction where the onboard solution had skipped the previous ground state update. RTC-6 was performed nominally using the ground-based targets. The team noted that with small burns and sensitive dynamics, small changes to navigation states can impact targeter and EI performance driving changes to ground vs. onboard target selection.

Table 17: RTC-6 Targeting Results

Targeting Pass	Convergence Status	# of Global Iterations	ICRF ΔV (ft/s)	Burn Plan ICRF ΔV (ft/s)	Trajectory Constraints
Preliminary	CONVERGED	2	-0.933 -0.210 0.912 *Magnitude:* *1.322*	-0.715 0.349 0.748 *Magnitude:* *1.092*	EI: Alt, HTL, VTL
Intermediate	CONVERGED	2	-0.828 -0.199 0.655 *Magnitude:* *1.074*	-0.715 0.349 0.748 *Magnitude:* *1.092*	EI: Alt, HTL, VTL
Final	CONVERGED	2	-0.842 -0.201 0.659 *Magnitude:* *1.087*	-0.683 0.150 0.857 *Magnitude:* *1.106*	EI: Alt, HTL, VTL

CONCLUSION

The Artemis I test flight proved to be a successful validation of the Two-Level Targeter while raising new opportunities for study and improvement. All of the in-flight targeting passes were successful and compared well with ground predictions. Iteration counts did not exceed 3 and the system performance resulted in a successful return to the Earth Interface for Entry. Future work

will explore minor discrepancies and expand on detailed targeting performance while improving robustness as the team turns its focus toward the Artemis II mission.

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